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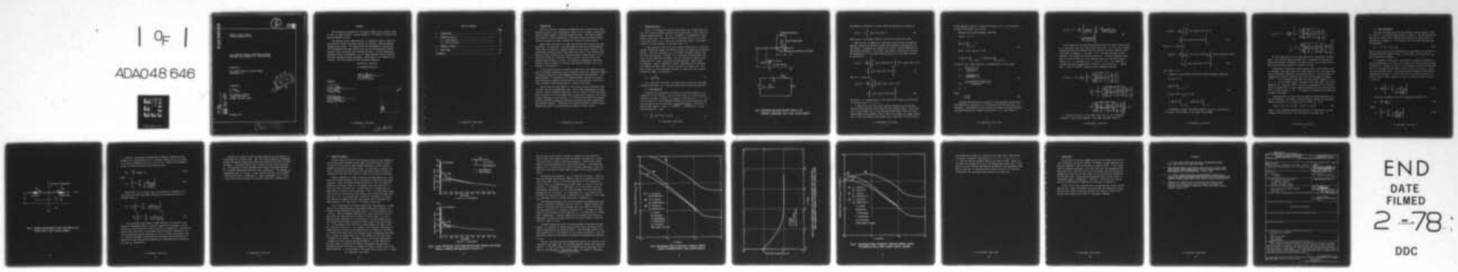

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STEP POTENTIAL AND BODY CURRENT NEAR A BURIED HORIZONTAL BARE CONDUCTOR IN A TWO-LAYER EARTH

Prepared for

U.S. Naval Electronic Systems Command
Washington, D.C.

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FOREWORD

This document was prepared for the Special Communications Project Office of the U. S. Naval Electronic Systems Command by IIT Research Institute under Contract N00039-76-C-0141.

The technical effort reported herein is intended to support studies of the electrical safety of terminal grounds for the Navy's proposed Seafarer communications system. This report covers the development of expressions for step potential and body current which may be experienced near Seafarer grounds, using a two-layer earth conductivity model. The derivations were provided to other investigators (i.e., R. Heppe, Computer Sciences Corporation) who performed extensive parametric calculations of the potentials and currents. The latter effort has been published separately.

Respectfully submitted,

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1. INTRODUCTION

Design of the Navy's Seafarer ELF Communications system has been accompanied by studies of the environmental effect of such a system, including the electric safety aspects of Seafarer ground terminals. The study presented here includes a refined formulation of the body current which may be experienced by a person or animal standing near a Seafarer ground terminal.

Body current can exist in a person near the Seafarer system by two basic mechanisms: (1) induction -- from the system's time varying electromagnetic field, and (2) conduction -- through contact with the earth's surface. Conducted body current may result from either the electric field induced in the earth by current flowing in the insulated Seafarer antenna cables, or from the fields caused by a conductive flow of current into the earth at the antenna ground terminals, or both. The conductive component of the earth electric field is dominant at locations near Seafarer grounds, and is the subject of this analysis.

In this study the earth is modeled as consisting of two separate layers, each of different conductivity, which represents the earth's electrical properties more accurately than the homogeneous earth model used heretofore. The ground terminal is represented by a buried horizontal bare wire of length L, and electrostatic solutions are derived for the step potential, earth resistance, and body current experienced by a person in the field.

The two-layer solution applies to the current carrying electrode buried in either the top or bottom earth layer. This allows consideration of cases such as a region of bedrock covered by a layer of topsoil in which the ground wire is buried, or of a thin upper layer of moist soil overlying a drier layer in which the ground wire is buried. It is believed that these study results permit a realistic assessment of the body currents which may be experienced near Seafarer grounds. In addition, the formulation applies to body currents produced near power line counterpoise structures or tower grounds.

2. THEORETICAL BASIS

Figure 1 illustrates the two-layer earth model and its equivalent circuit for a person or animal walking on the earth surface in the vicinity of Seafarer ground terminals. The soil is assumed to be homogeneous in both layers of the earth. The conductivity of the upper layer is σ_1 and that of the lower layer is σ_2. A bare wire carrying the current I is buried at a depth d, and the thickness of the upper layer is h.

In the equivalent circuit, the step potential denoted by V_s is the difference in potential between two feet of a person (or animal) at the earth's surface. The earth resistance, R_e, is the input resistance looking into the earth at the points of contact. R_b is the body resistance which typically is about 1000 ohms for humans. For the conservative analysis presented here, all contact resistance has been neglected. Under normal circumstances, however, substantial contact resistance will be provided, for example, by shoes, socks, dry skin, dry grass or leaves, etc. The body current, I_B, passing through the legs of a person for the situation depicted in Figure 1 is therefore,

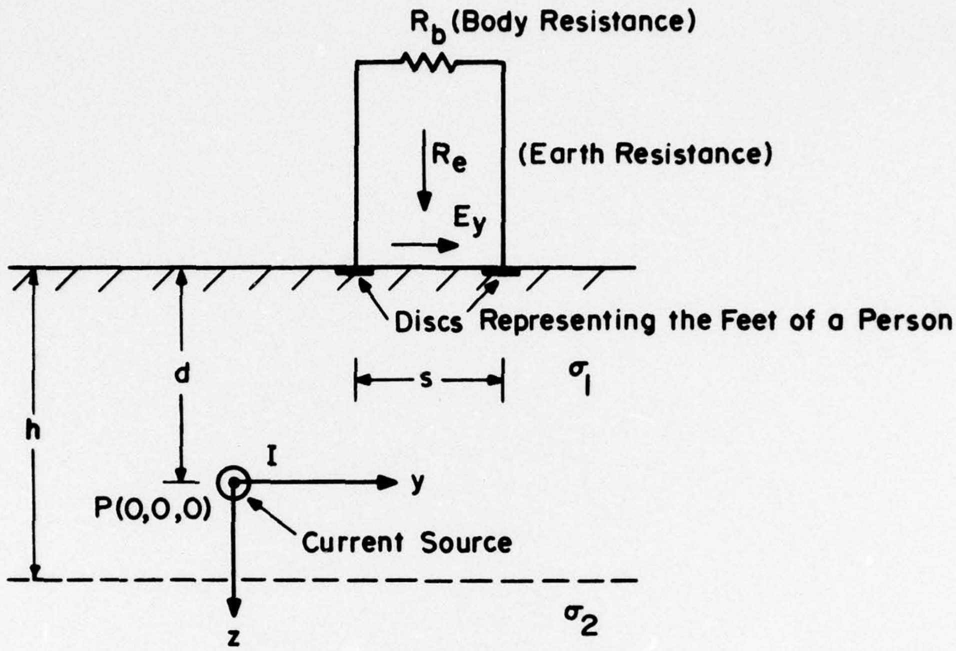
$$I_B = \frac{V_s}{(R_e + R_b)} \tag{1}$$

For a given body resistance, the body current increases as the earth resistance decreases, and is directly proportional to the step potential.

2.1 Step Potential

To obtain the electrostatic solutions for the step potential, it is convenient to first consider a point current source or an electrode energized by a current I_o situated, for example, at the point $P(x = y = z = 0)$ in a uniform earth. The fundamental potential function obtained from the Laplace equation for a point source in a uniform earth at a distance R is given by A/R, where $A = I_o/4\pi\sigma$, $R = \sqrt{\rho^2+z^2}$, $\rho = \sqrt{x^2+y^2}$, and σ is the earth conductivity. Since

$$\frac{1}{R} = \int_0^\infty J_o(\rho\lambda) \exp(\pm \lambda z)\, d\lambda, \tag{2}$$



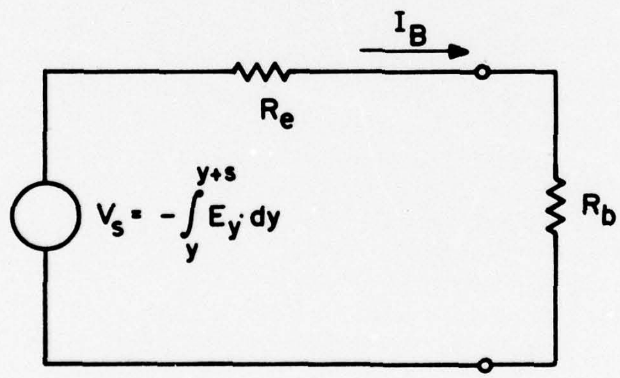


Fig. 1 DIAGRAM AND EQUIVALENT CIRCUIT OF PERSON STANDING ON A TWO-LAYER EARTH

the potential function for a uniform earth may therefore be expressed as

$$\phi(\rho,z) = A \int_0^\infty J_o(\rho\lambda) \exp(\pm\lambda z)\, d\lambda \tag{3}$$

where $J_o(\rho\lambda)$ is the Bessel function of the first kind and zero order.

When the earth is modeled as a two-layer stratification, the general potential function as derived by Sunde[1] may be obtained from Equation 3 by multiplying its integrand by a function $M(\lambda)$ which is then determined from the boundary conditions. As a result, the potential functions for the present problem $\phi_I(\rho,z)$ in the upper layer and $\phi_{II}(\rho,z)$ in the lower layer may be expressed as

$$\phi_I(\rho,z) = \frac{I_o}{4\pi\sigma_1} \left\{ \int_0^\infty J_o(\rho\lambda) \exp(\pm\lambda z)\, d\lambda + \int_0^\infty M_1(\lambda)\, J_o(\rho\lambda) \exp(-\lambda z)\, d\lambda \right.$$
$$\left. + \int_0^\infty N_1(\lambda)\, J_o(\rho\lambda) \exp(\lambda z)\, d\lambda \right\} \tag{4}$$

for $-d < z < (h-d)$ and

$$\phi_{II}(\rho,z) = \frac{I_o}{4\pi\sigma_1} \left\{ \int_0^\infty M_2(\lambda)\, J_o(\rho\lambda) \exp(-\lambda z)\, d\lambda \right.$$
$$\left. + \int_0^\infty N_2(\lambda)\, J_o(\rho\lambda) \exp(\lambda z)\, d\lambda \right\} \tag{5}$$

for $(h-d) < z < \infty$ respectively, if the current point source I_o is situated in the upper layer (i.e., $d < h$).

In Equation 4, the first term is usually referred to as the primary field, and the second and third terms are the secondary fields. The primary field in the present case is the field resulting directly from the current source, whereas the secondary field is due to the currents or charges induced on or in the soil medium by the primary field. Note that in the first term

of this equation, $\exp(\lambda z)$ is used in the region $-d \leq z \leq 0$, and $\exp(-\lambda z)$ is used in the region $0 \leq z \leq (h-d)$.

Matching the following boundary conditions

$$\begin{aligned}
&\phi_{II}(\rho, z = \infty) = 0 \\
&\frac{\partial}{\partial z}\phi_1(\rho,z)\bigg|_{z=-d} = 0 \\
&\phi_I(\rho, z = h-d) = \phi_{II}(\rho, z = h-d) \\
&\sigma_1 \frac{\partial}{\partial z}\phi_I(\rho,z)\bigg|_{z=(h-d)} = \sigma_2 \frac{\partial}{\partial z}\phi_{II}(\rho,z)\bigg|_{z=(h-d)},
\end{aligned} \tag{6}$$

a system of four linear equations is obtained which, in turn, gives

$$\begin{aligned}
M_1 &= \frac{\exp[2\lambda(h-d)] + k}{\exp(2\lambda h) - k} \\
N_1 &= k\left[\frac{\exp(2\lambda h) + 1}{\exp(2\lambda h) - k}\right] \\
M_2 &= \frac{(1+k)\{\exp(2\lambda h) + \exp[2\lambda(h-d)]\}}{\exp(2\lambda h) - k} \\
N_2 &= 0
\end{aligned} \tag{7}$$

where

$$k = \frac{\sigma_1 - \sigma_2}{\sigma_1 + \sigma_2} \tag{8}$$

Inserting the expressions of Equation 7 into Equations 4 and 5 yields the potentials at any point (ρ, z) in the upper layer and lower layer, respectively. The potential at the surface of the earth is obtained from the resultant expression of Equation 4 by setting $z = -d$. This leads to

$$\phi_I(\rho, z=-d) = \frac{I_o}{2\pi\sigma_1}\left\{\frac{1}{\sqrt{\rho^2+d^2}} + \sum_{n=1}^{\infty} k^n\left(\frac{1}{\sqrt{\rho^2+(2nh-d)^2}} + \frac{1}{\sqrt{\rho^2+(2nh+d)^2}}\right)\right\} \tag{9}$$

This expression gives the surface potential due to a point current source, I_o, in the upper layer at a depth d from the surface. For the case of present interest, the buried conductor carrying a current I extends along the x-axis (see Figure 1) between x = -L/2 and x = L/2. To obtain the total surface potential, the superposition theory may be used. The total potential at the earth's surface is the sum of the potentials due to all the point current sources at $x = x'$ extending from $x' = -L/2$ to $x' = L/2$. This summation is achieved through the integration of Equation 9 with respect to x'. Noting that $\rho = \left[(x-x')^2 + y^2\right]^{1/2}$, Equation 9 after integration becomes

$$\phi_I(x,y,z=-d) = \frac{I}{2\pi L\sigma_1}\left[\ln\left(\frac{\sqrt{\left(\frac{L}{2}+x\right)^2 + y^2 + d^2} + \left(\frac{L}{2}+x\right)}{\sqrt{\left(\frac{L}{2}-x\right)^2 + y^2 + d^2} - \left(\frac{L}{2}-x\right)}\right)\right.$$
$$+ \sum_{n=1}^{\infty} k^n\left\{\ln\left(\frac{\sqrt{\left(\frac{L}{2}+x\right)^2 + y^2 + \left(2\,nh+d\right)^2} + \left(\frac{L}{2}+x\right)}{\sqrt{\left(\frac{L}{2}-x\right)^2 + y^2 + \left(2\,nh+d\right)^2} - \left(\frac{L}{2}-x\right)}\right)\right.$$
$$\left.\left. + \ln\left(\frac{\sqrt{\left(\frac{L}{2}+x\right)^2 + y^2 + \left(2\,nh-d\right)^2} + \left(\frac{L}{2}+x\right)}{\sqrt{\left(\frac{L}{2}-x\right)^2 + y^2 + \left(2\,nh-d\right)^2} - \left(\frac{L}{2}-x\right)}\right)\right\}\right] \tag{10}$$

If the buried wire is in the lower layer (i.e., $d > h$), the general solutions of the Laplace equation in the upper and lower layers are

$$\phi_I(\rho,z) = \frac{I}{4\pi\sigma_1}\left\{\int_0^\infty M_1(\lambda)\, J_o(\rho\lambda)\, \exp(-\lambda z)\, d\lambda + \int_0^\infty N_1(\lambda)\, J_o(\rho\lambda)\, \exp(\lambda z)\, d\lambda\right\} \tag{11}$$

for $-d < z < -(d-h)$ and

$$\phi_{II}(\rho,z) = \frac{1}{4\pi}\left\{\frac{1}{\sigma_2}\int_0^\infty J_o(\rho\lambda)\, \exp(-\lambda z)\, d\lambda + \frac{1}{\sigma_1}\int_0^\infty N_2(\lambda)\, J_o(\rho\lambda)\, \exp(\lambda z)\, d\lambda + \frac{1}{\sigma_1}\int_0^\infty M_2(\lambda)\, J_o(\rho\lambda)\, \exp(-\lambda z)\, d\lambda\right\} \tag{12}$$

for $-(d-h) < z < \infty$.

Equations 11 and 12 must satisfy the following boundary conditions:

$$\begin{aligned}
&\phi_{II}(\rho,z=\infty) = 0 \\
&\left.\frac{\partial}{\partial z}\phi_I(\rho,z)\right|_{z=-d} = 0 \\
&\phi_I(\rho,z=h-d) = \phi_{II}(\rho,z=h-d) \\
&\left.\sigma_1\frac{\partial}{\partial z}\phi_I(\rho,z)\right|_{z=h-d} = \left.\sigma_2\frac{\partial}{\partial z}\phi_{II}(\rho,z)\right|_{z=h-d}
\end{aligned} \tag{13}$$

Proceeding as before, the surface potential due to a current source, I, having a finite length L in the lower layer becomes

$$\phi_I(x,y,z=-d) = \frac{I(1+k)}{2\pi L\sigma_1}\left[\ln\left(\frac{\sqrt{\left(\frac{L}{2}+x\right)^2+y^2+d^2}+\left(\frac{L}{2}+x\right)}{\sqrt{\left(\frac{L}{2}-x\right)^2+y^2+d^2}-\left(\frac{L}{2}-x\right)}\right)\right. \tag{14}$$

$$\left.+\sum_{n=1}^{\infty} k^n \ln\left(\frac{\sqrt{\left(\frac{L}{2}+x\right)^2+y^2+\left(2\,nh+d\right)^2}+\left(\frac{L}{2}+x\right)}{\sqrt{\left(\frac{L}{2}-x\right)^2+y^2+\left(2\,nh+d\right)^2}-\left(\frac{L}{2}-x\right)}\right)\right]$$

Note that Equations 10 and 14 have been given in Reference 2 without proof. The brief derivation presented here, in addition to verifying the equations presented in Reference 2 as being correct, can be used to obtain the earth resistance presented in Section 2.2 below.

Examination of Equations 10 and 14 reveals that if the current source is situated in the upper layer, the surface potential for a two-layer earth may be calculated by adding the surface potential for a uniform earth of conductivity σ_1 and the potentials due to an infinite number of images, $k, k^2, \ldots k^n$ at distances $2\,nh \pm d$ below the earth surface, where $n = 1, 2, 3, \ldots \infty$. If the current source is located in the lower layer, the surface potential for a two-layer earth is the sum of the potential for a uniform earth of conductivity $(\sigma_1 + \sigma_2)/2$ and the potentials due to an infinite number of virtual sources, $k, k^2, \ldots k^n$ located at distances $2\,nh+d$ below the surface of the earth.

Using equations 10 and 14, the step potential defined previously can now be determined. For example, the step potential along the line perpendicular to the wire (i.e., y-axis) near its center (x = 0) is

$$V_s(y_0) = \phi_I(x=0,\ y=y_0+\tfrac{s}{2}) - \phi_I(x=0,\ y=y_0-\tfrac{s}{2}) \tag{15}$$

where s is the separation between the two feet of a person and y_0 is the distance from the wire at $x=0$ to the center of the foot step.

2.2 Earth Resistance

The earth resistance which has been defined in the equivalent circuit of Figure 1 is illustrated geometrically in Figure 2. For the present problem, the two metallic discs represent the two feet of a person which are separated by a distance s. In its general form, the earth resistance may be expressed as

$$R_e = R_1 + R_2 - (M_{12} + M_{21}) \qquad (16)$$

where R_1 and R_2 are the self resistances and M_{12} and M_{21} are the mutual resistances of the two metallic discs. In this case, $R_1 = R_2$ and $M_{12} = M_{21}$ due to geometrical symmetry.

The potential at the earth's surface due to a spherical electrode of radius a energized by a current I_o at a depth d has been obtained and given by Equation 9. Setting d = 0 and ρ = a in Equation 9 would give the potential at a hemispherical electrode of radius a due to a current I_o flowing into the electrode itself. Following the same procedures as described for hemispheric electrodes, it can be shown that the surface potential at a metallic disc of radius a due to a current I_o flowing into the same disc is given by

$$V_1 = \frac{I_o}{4a\sigma_1}\left\{1 + 2\sum_{n=1}^{\infty} \frac{k^n}{\sqrt{1 + \left(\frac{2nh}{a}\right)^2}}\right\} \qquad (17)$$

With this information, the self resistance by definition is

$$R_1 = \frac{V_1}{I_o} = \frac{1}{4a\sigma_1}\alpha_s \qquad (18)$$

where

$$\alpha_s = \left\{1 + 2\sum_{n=1}^{\infty} \frac{k^n}{\sqrt{1 + \left(\frac{2nh}{a}\right)^2}}\right\} \qquad (19)$$

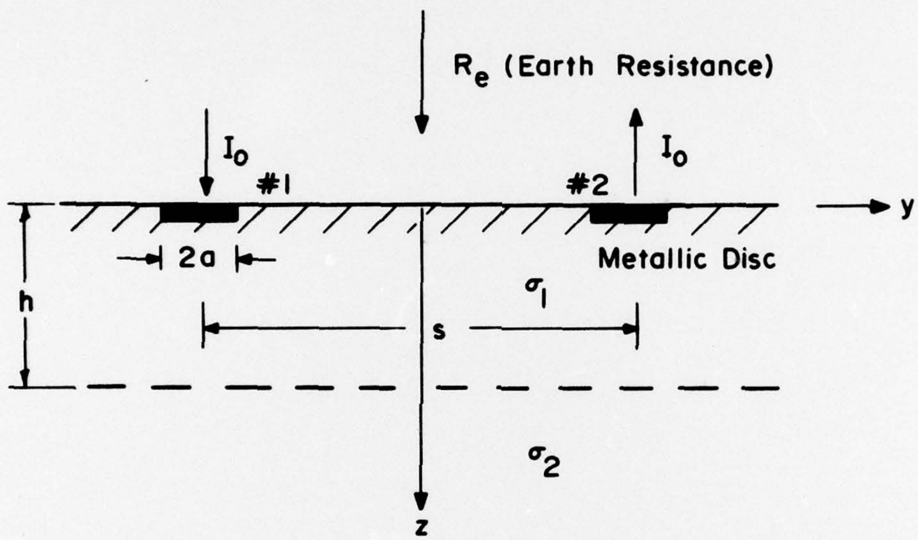


Fig. 2 EARTH RESISTANCE FOR TWO METALLIC DISCS ON A TWO-LAYER EARTH

Similarly, the mutual resistance may be obtained by determining the potential at a second metallic disc, a distance s away, due to the current I_o at the first metallic disc (i.e., $d = 0$, $\rho = s$). Denoting this potential by V_{12}, the mutual resistance may be obtained from

$$M_{12} = \frac{V_{12}}{I_o} = \frac{1}{2\pi\sigma_1 s} \alpha_m \tag{20}$$

where

$$\alpha_m = \left\{ 1 + 2 \sum_{n=1}^{\infty} \frac{k^n}{\sqrt{1 + \left(\frac{2nh}{s}\right)^2}} \right\} \tag{21}$$

Noting that $R_1 = R_2$ and $M_{12} = M_{21}$, the insertion of Equations 18 - 21 into Equation 16 gives the earth resistance for two metallic discs on a two-layer earth as

$$R_e = \frac{1}{2\sigma_1} \left\{ \frac{1}{a} + 2 \sum_{n=1}^{\infty} \frac{k^n}{\sqrt{a^2 + (2nh)^2}} \right\} - \frac{1}{\pi\sigma_1} \left\{ \frac{1}{s} + 2 \sum_{n=1}^{\infty} \frac{k^n}{\sqrt{s^2 + (2nh)^2}} \right\} \tag{22}$$

It has previously been shown by Sunde[1] that the self and mutual resistances for two metallic discs of radius a separated by a distance s on the surface of a uniform earth are $1/4a\sigma_1$ and $1/2\pi\sigma_1 s$, respectively. Equations 18 and 20 reveal the effect of a two-layer earth on the earth resistance is entirely governed by the two quantities, α_s and α_m, given by Equations 19 and 21. The self and mutual resistances for a two-layer earth can therefore be obtained from the uniform earth expressions by multiplying these expressions by α_s and α_m, respectively.

Equation 22 is used for earth resistance because the disc geometry is a good model for a person's feet. The first term of Equation 22 represents the self resistance, whereas the second term represents the effect of mutual resistance. The mutual effects tend to reduce the total earth resistance, R_e. The reduction in earth resistance due to mutual resistance decreases as s increases and becomes negligible when s approaches ∞. As expected, as h approaches zero, $R_e = 1/2a\sigma_2 - 1/\pi\sigma_2 s$, and the two-layer earth resembles a uniform earth with a conductivity σ_2. When h approaches ∞, $R_e = 1/2a\sigma_1 - 1/\pi\sigma_1 s$, the earth resistance for a uniform earth with a conductivity σ_1.

3. NUMERICAL EXAMPLES

Several examples illustrate the functional trends of such parameters as the upper layer thickness, burial depth of ground conductor, conductivities of the two layers and horizontal separation as they relate to maximum step potentials and body currents. As discussed in previous sections, a quantitative description of possible body currents provides an indication of the electrical safety of a particular ground system design.

Based on Equation 15, Figure 3 presents the step potential as a function of horizontal separation in the vicinity of a 4000 meter long ground conductor. Figure 3(a) shows the step potential for the case where the thickness of the upper layer, h, is 3 meters, while the results for h = 5 meters are given in Figure 3(b). In both cases it is assumed that the separation of a person's feet is one meter. This is a conservative assumption, since most individuals do not separate their feet by one meter when they walk. It is also assumed that a current of 100 amperes is flowing into the ground conductor and that the conductivities of the upper and lower layers are 10^{-2} mho/m and 5×10^{-4} mho/m, respectively.

Closer inspection of the figures reveals that step potential, in addition to its strong dependence on the depth of the ground conductor, is a function of the thickness of the upper layer, h, and both conductivities, σ_1 and σ_2. When the basement conductivity is lower than that of the surface layer, the step potential is higher for smaller values of h and d. Near the ground conductor (x = 0, see Figure 1), the step potential has its largest value at equal distances on either side of the ground conductor. This distance varies with d and h, being greater for larger values of d and small values of h. As an example, for a conductor 4000 meters in length carrying a current of 100 amperes buried at a depth of 1.82 meters (≈ 6 feet) in the upper layer of a two-layer earth, the maximum step potential is found to be about 0.36 volt if the thickness of the upper layer is assumed to be 3 meters. This would occur at the points approximately 3.5 meters on either side of the ground conductor. If the thickness of the upper layer is increased to 5 meters, the maximum step potential is decreased to about 0.26 volt at a distance 2.5 meters on either side of the ground conductor. If the thickness of the upper layer is kept at h = 5 meters,

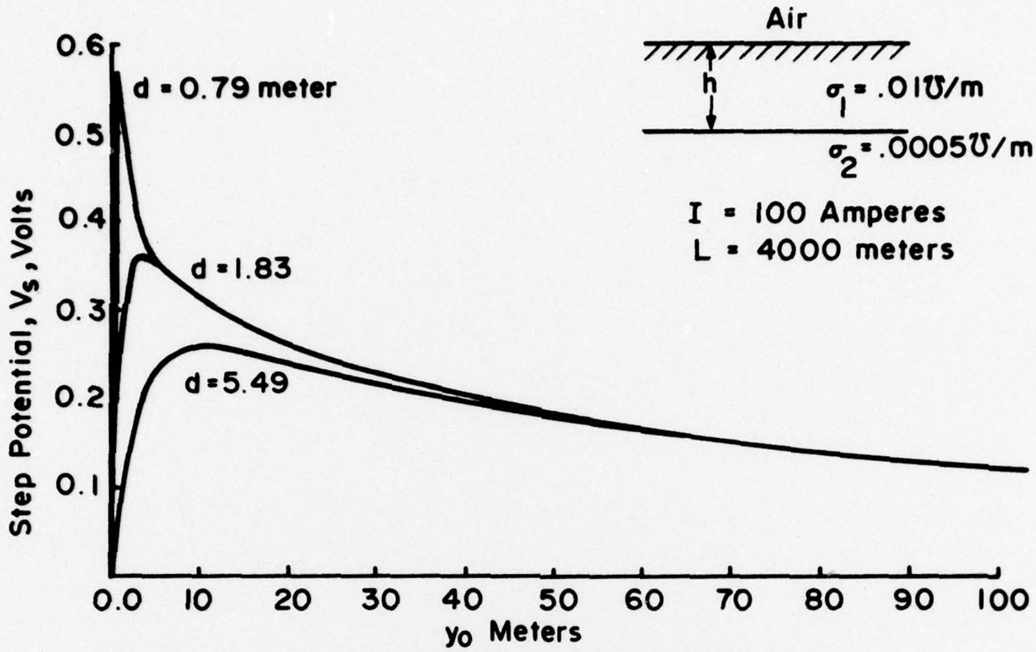


Fig. 3 a h = 3.0 meters

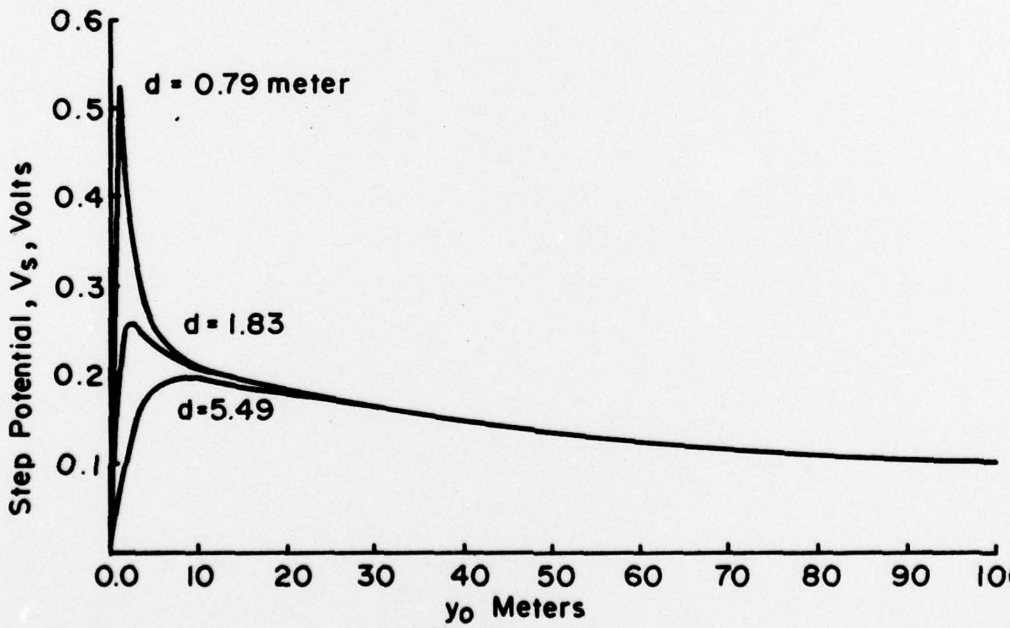


Fig. 3 b h = 5.0 meters

Fig. 3 STEP POTENTIAL FOR A ONE METER STEP VERSUS DISTANCE FROM A CONDUCTOR BURIED AT A DEPTH d

but the same current source is buried at a depth 0.76 meter below the earth surface, then Figure 3(b) shows the maximum step potential is about 0.525 volt within a meter of the ground conductor. These results differ greatly from those obtained from a uniform earth model: the maximum step potential for a uniform earth is simply inversely proportional to the conductivity of the earth and the length and depth of the buried ground conductor.

The maximum step potential, V_{max}, is important for safety. Figure 4 shows the maximum step potential (1 meter step) as a function of the thickness of the upper layer, h, for three combinations of soil conductivity. In every case, σ_1 is considered to be higher than σ_2. Also, for this calculation, I = 100 amperes, L = 4000 meters, and d = 0.76 meter are used. The maximum step potential for all cases presented in Figure 4 decreases monotonically as h increases. As h approaches zero, V_{max} reduces to that obtained for a uniform earth with a conductivity, σ_2. When h is very large, V_{max} approaches that of a uniform earth with a conductivity σ_1.

The remaining parameter which must be evaluated to determine the body current is the earth resistance, R_e (see Figure 1). Applying Equation 22, Figure 5 illustrates the earth resistance for a disc radius of 0.05 meter and step separation of 1.0 meter as a function of h. The upper and lower conductivities assumed for this example are σ_1 = 0.01 mho/m and σ_2 = 0.0005 mho/m, respectively. The high conductivity of the upper layer basically determines the earth resistance except for very small values of h (on the order of 1 meter or less).

Through calculations similar to those presented in the previous paragraphs, it is possible to determine body current levels associated with a specific ground design and earth structure. Since the body current is linearly proportional to step potential as is evident by Equation 1, the calculated body current will be based on the maximum step potential and denoted as I_{max}.

Figure 6 shows the calculated maximum body current as a function of the thickness of the upper layer for the same parametric values used to develop Figure 4. In this calculation, it was assumed that the total body resistance, R_b, was 1000 ohms, a conservative figure. As Figure 6 illustrates,

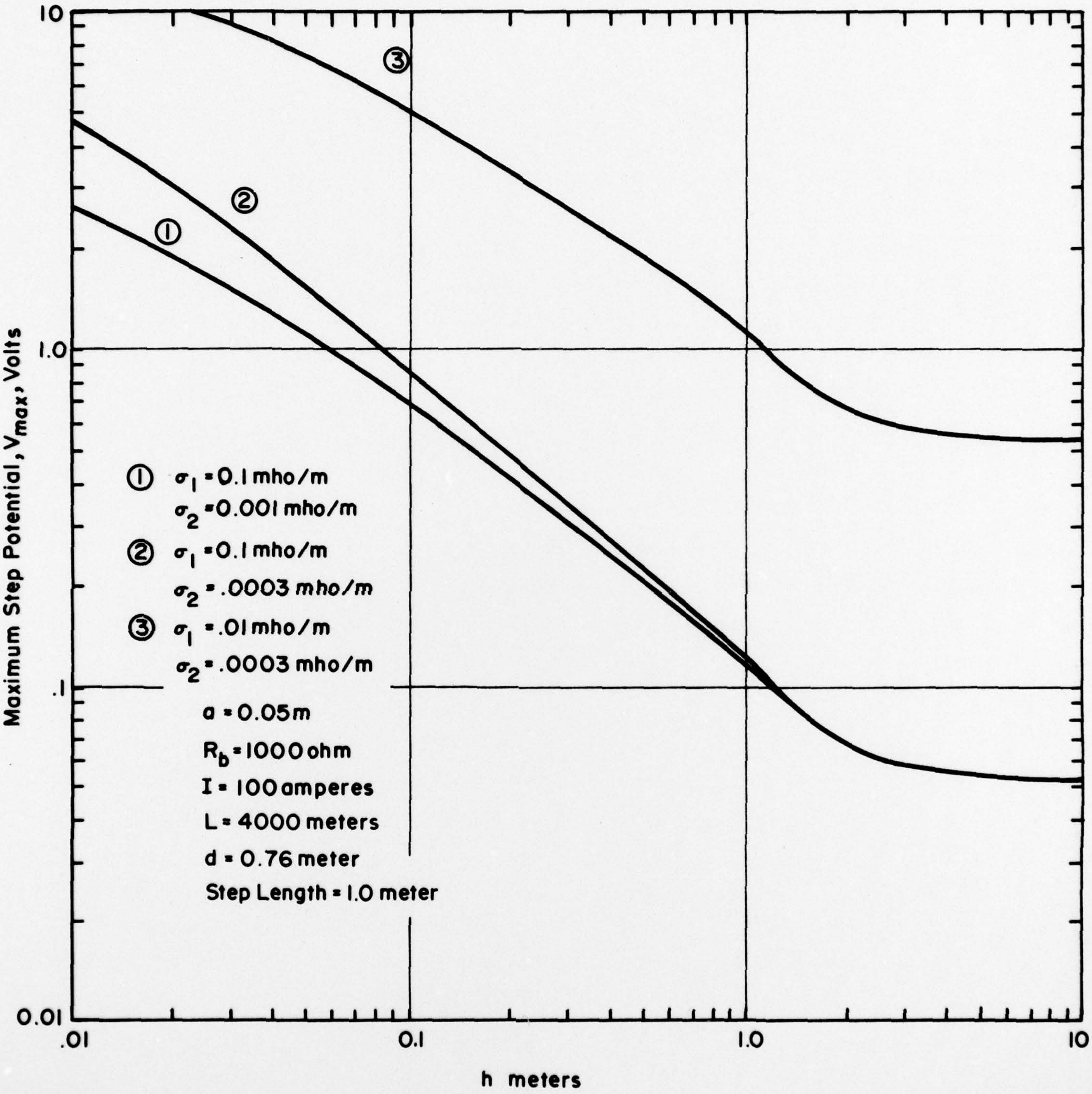


Fig. 4 MAXIMUM STEP POTENTIAL VERSUS UPPER LAYER THICKNESS FOR A TWO LAYER EARTH

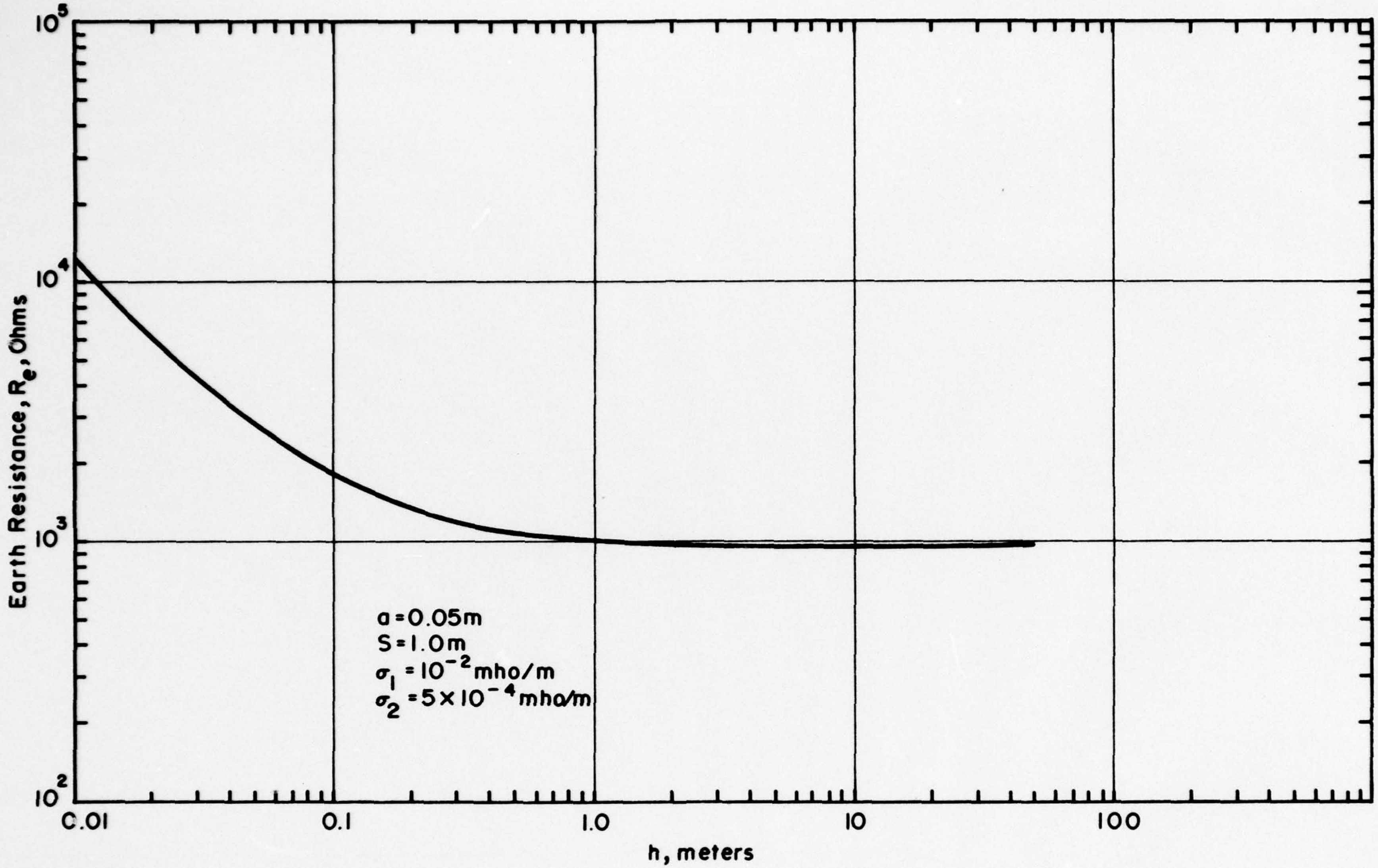


Fig.5 EARTH RESISTANCE OF A ONE-METER FOOT STEP ON A TWO-LAYER EARTH VERSUS THICKNESS OF UPPER LAYER

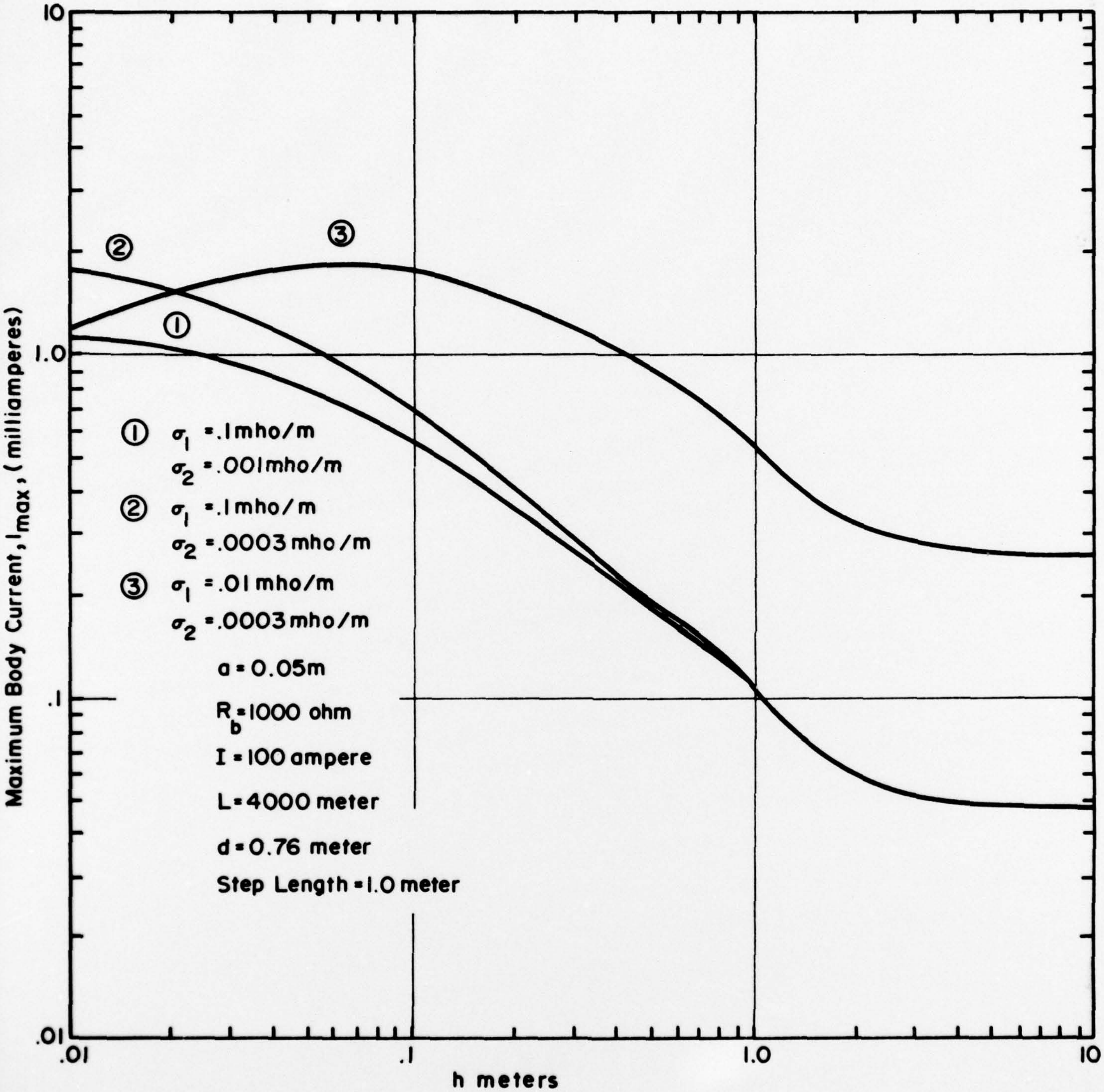


Fig. 6 MAXIMUM BODY CURRENT VERSUS UPPER LAYER THICKNESS FOR A TWO-LAYER EARTH MODEL

the maximum body current as a function of the upper layer thickness does not possess a monotonic relationship (i.e., $h = 0$, $\sigma = \sigma_2$, or $h = \infty$, $\sigma = \sigma_1$ are not absolute bounding cases for the body current). Hence, for the conditions assumed for curve 3, the maximum body current for $h = 0.08$ meter is actually greater than would be obtained for both bounding uniform earth structures. It should be noted, however, that for all cases considered here, the calculated body current is less than 2 ma.

4. CONCLUSIONS

The results of this work suggest a two-layer earth model more realistically represents the actual situation and defines an upper bound for the possible magnitude of body current near a Seafarer ground. In the several numerical examples presented, it has been shown that the maximum possible body current for a two-layer earth could be greater than predicted from a homogeneous earth analysis using either of the conductivities assumed for the two-layer case. A more detailed parametric study of body current is presented by Heppe in Reference 3. The Navy's criteria for the step potential and body current thresholds are discussed in Reference 4.

For all of the cases presented here, the maximum body current calculated was 2 ma. These calculations were made under the conservative assumptions of zero contact resistance, maximum step potential location, and a nominal burial depth of 30 inches for the ground conductor.

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The problem of electrical safety in the vicinity of the Navy's proposed Seafarer antenna is studied. The electrostatic solutions for the step potential and earth resistance are derived for a two-layer earth model from which the body current is calculated. It has been found that under certain conditions the maximum body current predicted by a two-layer earth model is greater than that obtained from the uniform earth analysis.

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